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Cutting edge

Goddard's Emerging Technologies

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in this issue:

Atom Optics Come of Age

Goddard Scientist Babak Saif and the Center-Designed Laser System

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Photo Credit: Pat Izzo

Volume 8 • Issue 4 • Summer 2012

Atom Optics Come of Age

Goddard Establishes Strategic Collaboration with Stanford University

One of the world's largest atom interferometers — a 33-foot drop tower in the basement of a Stanford University physics laboratory — soon will begin testing whether this pioneering technology, coupled with a highly precise Goddard-designed laser system, can one day directly detect what so far has remained imperceptible and experimentally elusive: gravitational waves or ripples in space-time caused by cataclysmic events, including even the Big Bang itself.

The drop-tower test is just part of a much larger effort involving Stanford University, AOSense, Inc., a privately owned Sunnyvale, Calif.-based firm specializing in atom optics-based sensors, and Goddard researchers. They began collaborating more than two years ago to deploy this emerging, highly precise measurement technology in space.

"We've been working with Stanford and AOSense on how to implement this technology for space applications and the good news is it's proving very compatible for space," said Goddard's Lee Feinberg, a member of the team.

Atom interferometry or atom optics could be used for a variety of space applications, but the team so far has used support from Goddard's Internal Research and Development program and NASA's Center Innovation Fund to advance gravitational-wave sensor technologies. The team also has created a potential mission and is now requesting additional NASA funding to enhance the concept.

Although astrophysical observations have implied the existence of gravitational waves, no instrument or observatory, including the ground-based Laser Interferometer Gravitational-Wave Observatory, has ever directly detected them.

Predicted by Albert Einstein's general theory of relativity, gravitational waves occur when massive celestial objects move and disrupt the fabric of space-time around them. By the time these waves reach Earth, they are so weak that the planet expands and contracts less than an atom in response. This makes their detection with ground-based equipment more challenging because environmental noise, like ocean tides and earthquakes, can easily swamp their faint murmurings.

Should scientists confirm their existence, they say the discovery would revolutionize astrophysics, giving them a new tool for studying everything from

The 33-foot drop tower at Stanford University will be used to test a Goddard-designed laser system that could be used in future atom-optics instruments. (Photo Credit: Stanford University)

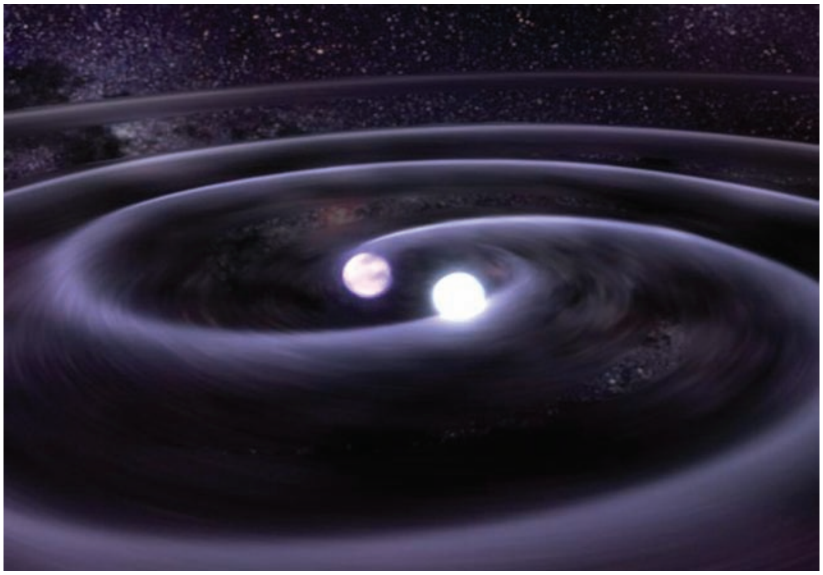
inspiralling black holes to the early universe before the fog of hydrogen plasma cooled to give way to the formation of atoms.

Technological Panacea

"I've been following this technology for a decade," said Bernie Seery, a Goddard executive who was instrumental in establishing the strategic partnership with Stanford University professor Mark Kasevich, who is credited with pushing the frontiers of atom interferometry. In 2001, NASA competitively selected a proposal to demonstrate atom-optics technologies on the International Space Station, but canceled it and other fundamental physics projects due to budgetary pressures.

"The technology has come of age," Seery added, alluding to progress made since the project's cancellation. "It opens up a wealth of possibilities. This technology will move ahead very quickly now."

Continued on page 3


Cataclysmic events, such as this artist's rendition of a binary-star merger, are believed to create gravitational waves that cause ripples in space-time.

Atom interferometry, once a lab curiosity when four independent teams in the U.S. and Germany built the first devices in the early 1990s, has since evolved into a technological panacea for everything from measuring gravitational fields to steering submarines and airplanes, uncovering caches of oil and precious stones, and finding nuclear materials stashed inside shipping containers.

Interested in its potential to dramatically improve navigation, the U.S. Defense Advanced Research Projects Agency (DARPA) began investing in the technology several years ago. Once DARPA perfects its navigational sensors, NASA can leverage these devices to navigate around a near-Earth asteroid, for example, and measure its gravitational field to deduce its composition, Seery said. It's also ripe for use in commercial gyroscopes, accelerometers, gravity gradiometers, and highly precise clocks — any application demanding exacting measurements, he added.

Like Optical Interferometry

At its core, atom interferometry works much like optical interferometry, a 200-year-old technique widely used in science and industry to measure small displacements in objects. With this technique, a beamsplitter divides light into two beams. One beam of light reflects off a flat mirror that is fixed in place on one arm of an interferometer. The other beam reflects off another mirror attached to a mechanism that moves it a very short distance away from the beamsplitter. The two beams then recombine at the end of the optical path.

Because the path that one beam travels is fixed in length and the other is constantly changing as its mirror moves, the signal that exits the device is the result of these two beams "interfering" with each other. Scientists use the resulting interference pattern to determine fine details in spectra, measure the diameters of nearby stars, and check the surfaces of telescope mirrors for imperfections, among many other applications.

Atoms as Waves

Atom interferometry, however, hinges on quantum mechanics, the theory that describes how matter behaves at sub-microscopic scales. Just as waves of light can act like particles called photons, atoms can be cajoled into acting like waves if cooled to near absolute zero. At those frigid temperatures, which scientists achieve by firing a laser at the atom, its velocity slows to nearly zero. By firing another series of laser pulses at laser-cooled atoms, scientists put them into what they call a "superposition of states." In other words, the atoms have different momentums permitting them to separate spatially and be manipulated to fly along different trajectories. Eventually, they cross paths and recombine at the detector — just as in a conventional interferometer.

"Atoms have a way of being in two places at once, making it analogous to light interferometry," Kasevich explained.

The power of atom interferometry is its precision. If the path an atom takes varies by even a picometer, an atom interferometer would be able to detect the difference. Given its atomic-level precision, "gravity-wave detection is arguably the most compelling scientific application for this technology in space," said physicist Babak Saif, who is leading the effort at Goddard.

Strategic Partnership

Since joining forces, the team has designed a powerful, narrowband fiber-optic laser system that it plans to test at Stanford's tower interferometer this summer. Close scientifically to what the team would need to detect theoretical gravitational waves, the technology would be used as the foun-

Continued on page 10

Volume 8 • Issue 4 • Summer 2012

Spectrometer-on-a-Chip

Goddard Team to Demonstrate Miniaturized CIRS-Like Instrument

The Goddard-built Composite Infrared Spectrometer (CIRS) is big. It's powerful. And it discovered, among other things, that Saturn's mysterious moon, Enceladus, was one of the very few worlds in the solar system that radiated several gigawatts of heat into space, primarily along prominent fractures dubbed "tiger stripes."

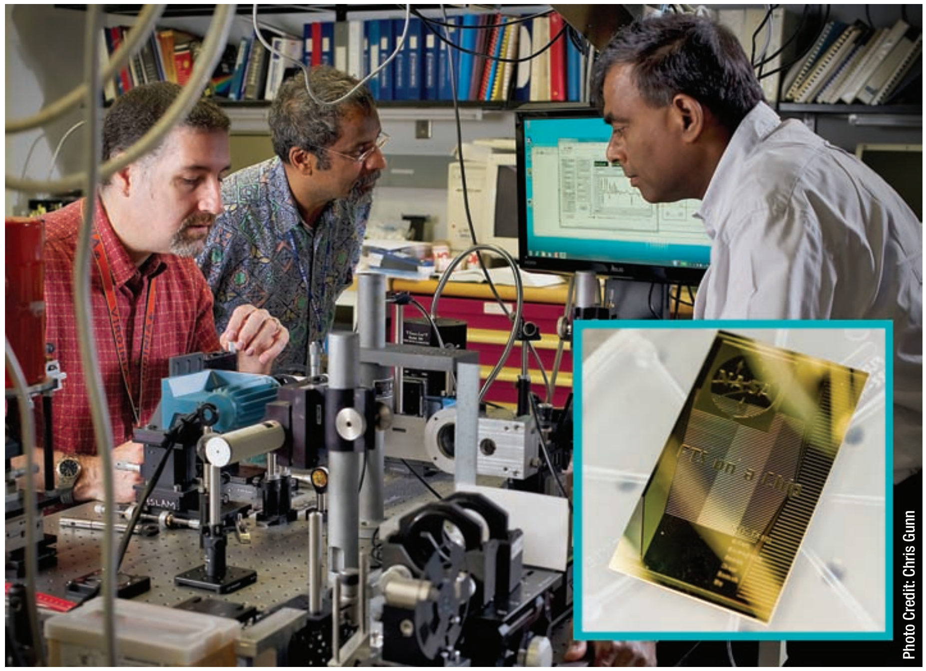


Photo Credit: Chris Gunn

George Shaw (left), Shahid Aslam (center), and Tilak Hewagama (right) are testing their spectrometer-on-a-chip (shown in the inset) that could dramatically reduce the size of future instruments.

If a team of Goddard technologists succeeds, however, scientists in the future won't observe these far-flung worlds with instruments the size of dishwashers. Rather, they will make their discoveries with dramatically smaller, more efficient models whose critical components fit onto a silicon wafer and do not require moving parts to operate — unlike the breadbox-size components found inside CIRS, which flew on the Cassini-Huygens mission.

"The Holy Grail is reducing the number of moving parts, which will allow us to build lighter, smaller instruments," said team member John Allen. "The smaller the device, the better. That's where the power of our effort really begins to take off."

The potentially revolutionary Miniaturized Waveguide Fourier Transform Spectrometer (FTS), which, like CIRS, would be sensitive to the mid-infrared bands, is a greatly scaled down version of the Michelson-type FTS commonly used to study the spectra of planets and stars and identify their chemical makeup and other physical properties.

With traditional Michelson-type instruments, a beamsplitter takes the incoming light gathered by a telescope and divides it into two optical beams. One beam of light reflects off a flat mirror that is fixed in place on one arm of the instrument; the other reflects off another mirror, which is attached to a mechanism that moves the mirror a very short distance — typically a few millimeters — away from the beamsplitter. At the end of the optical path, the two beams recombine.

Because the path that one beam travels is fixed in length and the other is constantly changing as its mirror moves, the signal that exits the device is the result of these two beams "interfering" with one another. When analyzed with the Fourier transform, a mathematical theorem invented by Joseph Fourier in 1811, the resulting interferogram produces a spectrum revealing the various wavelength frequencies emitted by the source.

Though this type of spectrometer is ubiquitous in science investigations, "obtaining an accurate spectrum with the instrument exacts a penalty in the form of mass, electrical power, and moving parts that can fail," explained Shahid Asalm, the principal investigator leading the effort funded by NASA's Center Innovation Fund and Goddard's Internal Research and Development program. To find berths on future planetary missions, instruments would have to be significantly smaller, lighter, and more capable, he said.

To lighten the load and reduce complexity, the team wants to replace the mirrors and associated hardware with a microscale photonic system featuring 60 hollow waveguides, or tunnel-like circuits, 10 times thinner than a human hair.

Continued on page 5

Etched inside a silicon wafer, these tiny circuits would carry out the job of more traditional Michelson-type spectrometers. The light would travel down these tiny tubes, hit a Y-junction, split, and then continue its journey down two separate channels. One beam would take a relatively straight path; the other would take a path that loops slightly to create a longer route. The two beams would then recombine to create one intensity point on an interferogram from which to derive a spectrum.

"The result is a spectrometer-on-a-chip that fits in the palm of a hand, excludes moving parts, and samples the complete inteferogram simultaneously," Aslam said. "In addition, the device does not require mechanical power to move the mirror, nor any bulky, high-precision free-space optics as in classical Fourier transform spectrometers. The significance of our research is that we're transforming how we propagate light. We're replacing large, high-precision optics with microscale light pipes."

Although researchers have reported creating a similar device tuned to the visible and near-infrared wavelength bands, no one has attempted it for instruments sensitive to mid- and long-infrared light. "When we do simulations, we find the physics are true. No rules are violated. In principal, we should be able to make a device like this," Aslam said, adding that he and his team, also including Co-Principal Investigator Tilak Hewagama and engineer George Shaw, plan to demonstrate the device by the end of the year.

Demonstrating that the approach can produce an interferogram is one challenge. The other will be in engineering an instrument that can take advantage of the micro optics and gather useful science. "This is embryonic," Allen agreed. "We'll need a few more years to advance this technology and I'm sure we'll encounter a lot of pitfalls. But we have to try to understand how these photonic circuits work efficiently," Asalm said, adding it took a Goddard team nearly 10 years to develop CIRS.

Should the group succeed, Aslam said the payoff will be huge, not only for NASA's science disciplines, but for biotechnology and other commercial applications. Asalm envisions using the technology for detecting anthrax and other life-threatening materials in trucks and shipping containers because of its potential to reduce the size of instruments for more mobile use. "Anywhere you're trying to remotely sense, I think this technology has a multitude of applications," Allen said. ❖

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New Tool to Identify Organics

While the spacecraft carrying NASA's next Mars rover hurdled through space for its early August encounter with the red planet, Goddard technologist Stephanie Getty received word that her team had won $1 million in NASA funding to mature a new space instrument to analyze complex organic material with a level of specificity available only with a well-equipped Earth-bound laboratory.

Under the three-year award by NASA's Planetary Instrument Definition and Development Program, the team will develop a two-step laser tandem mass spectrometer. It will be able to detect a wide range of non-volatile organics in complex mixtures, like those found in meteorites, and then determine the structure of selected molecules found in the sample. "This level of specificity could give scientists powerful insights into the origin of organic materials found in the outer solar system and how they evolved," Getty said.

Although NASA's Curiosity rover, and more specifically its Goddard-developed Sample Analysis at Mars (SAM) instrument suite, will search for volatile organic compounds when it begins operations, it will carry out its job by heating crushed rock samples in small oven cells. As it heats, the sample will begin to break down, releasing gases that SAM analyzes. Though effective at finding in-situ organic carbon, SAM's ovens can break chemical bonds, resulting in fragmentation and the loss of molecular information — the details that Getty's instrument is designed to preserve.

Getty's proposed instrument is an upgraded time-of-flight mass spectrometer, which creates charged molecules, called ions, using a laser pulse. It then detects those ions to determine the molecular weight of the compound and its chemical structure. Among other things, she and her team will equip the new instrument with ionization techniques that are gentler on the sample.

Better yet, the instrument will pack that much capability in a 12-inch package weighing only 11 pounds, 10 times smaller than commercial devices. "What we want to do is contribute to a systematic inventory of organic matter present in the solar system," Getty explained. "The question that I ultimately want to answer is whether those organics are indicative of habitability." ❖

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Volume 8 • Issue 4 • Summer 2012

Space-Age Materials One Atomic Layer at a Time

Goddard technologist Vivek Dwivedi (right) and his collaborator, University of Maryland professor Raymond Adomaitis (left), are shown here with a sample and the reactor that they will use to apply thin films onto the substrate using atomic layer deposition.

An emerging technology that promises to stop silver from tarnishing and allow computer chips to run faster is being studied as a potential solution for cracking three of NASA's thorniest engineering challenges.

Goddard technologist Vivek Dwivedi is collaborating with University of Maryland chemical engineering professor Raymond Adomaitis to show that atomic layer deposition (ALD) — a rapidly evolving technology for coating plastics, semiconductors, glass, Teflon, and a plethora of other materials — is a cost-effective tool for coating X-ray optics and "smart" radiators, and creating nanotube coatings to protect and strengthen spacecraft components.

The technique, first reported in the 1980s and later adopted by the semiconductor industry, involves placing a substrate material inside a reactor chamber and sequentially pulsing different types of precursor gases to create an ultrathin film whose layers are literally no thicker than a single atom. Among other uses, the resulting films improve computer memory, protect materials against corrosion, oxidation, and wear, and perform as batteries when deposited directly onto chips.

Though similar to chemical vapor deposition (CVD), another technique for applying thin films, ALD differs because the process is split into two half reactions, is run in sequence, and is repeated for each layer. As a result, technicians can accurately control the thickness and composition of the deposited films, even deep inside pores and cavities. This gives ALD a unique ability to coat in and around 3D objects. This advantage — coupled with the fact that technologists can create films at much lower temperatures than with CVD — has led many in the optics, electronics, energy, textile, and biomedical-device fields to replace older deposition techniques with ALD.

NASA, too, has caught the ALD bug. "It's really exciting," said Ted Swanson, the assistant chief for technology for mechanical systems. "This is an emerging technology that offers a wholly new way of laying down material less expensively."

While applications potentially abound, the team is using funding from Goddard's Internal Research and Development program and NASA's Center Innovation Fund to demonstrate three by year's end.

X-ray Optics

One potential beneficiary is X-ray astronomy. Goddard scientist Will Zhang has developed a technique for manufacturing low-cost, lightweight

Continued on page 7

mirrors needed to collect highly energetic X-rays, which only can be collected with curved mirrors nested inside an optical assembly.

Instead of custom fabricating these glass segments, as is traditional now, Zhang and his team proved that they could use flat sheets of very thin commercially available glass and slump them over a rounded mold to provide an exact optical prescription for collecting X-rays. Using this approach, Zhang manufactured 9,000 super-thin glass segments for NASA's Nuclear Spectroscopic Telescope Array mission, which NASA launched in early June (*CuttingEdge*, Winter 2012, Page 4).

Technicians could use ALD to apply highly reflective materials onto mirror surfaces because it uniformly coats 3D objects, like curved mirrors, of every size, shape, and orientation inside the reactor chamber, Dwivedi said. "This is in direct contrast to other techniques that typically require the surface to be in the line of sight in order for it to be properly coated," Zhang said. Because future X-ray observatories will require literally thousands of segmented mirrors, ALD would help drive down telescope costs because multiple mirrors could be coated at once, Dwivedi said.

Dwivedi and his team provided Zhang with ALD-coated thin films for testing. "We're working through some issues," Dwivedi said. "Though we still need to tweak the recipe, initial depositions succeeded, proving that ALD was viable for this application."

Passive Radiators

Another promising application is in the area of instrument cooling, Dwivedi said. Even in the vacuum of space, spacecraft instruments and components generate heat, potentially jeopardizing their performance should they overheat. Because mechanical-based radiators take up space and add weight, engineers have begun looking for alterative "smart" radiator coatings that passively emit heat when they reach a certain temperature. At least analytically, engineers have demonstrated that the approach would reduce an instrument's mass and power consumption.

These "smart radiators" are often made of flat pieces of aluminum coated with tungsten-doped vanadium in a process called "sputtering." Unfortunately, sputtering, like CVD, requires extremely high temperatures and doesn't always result in uniform coating. With ALD, however, designers wouldn't be restricted to flat radiator planes.

They could experiment with different approaches because ALD uniformly coats all types of substrate materials, regardless of shapes or sizes. Since beginning the R&D, the Goddard-led team has successfully coated a sample with layers of vanadium oxide, an experimental ALD recipe the team developed for this application.

Spacecraft Protection

Without question, the team's biggest challenge will be in nanomanufacturing boron-nitride nanotubes (BNNTs), Dwivedi said. BNNTs are a type of coating similar in structure to carbon nanotubes, tiny hollow tubes grown vertically on silicon, silicon nitride, titanium, and stainless steel. Under an electron microscope, they look like a shag rug.

Dwivedi believes BNNTs could be particularly effective at protecting spacecraft from the harmful effects of high-energy solar particles and meteorite impacts. "Boron nitride is one of the hardest materials in the world," Dwivedi said. "It also demonstrates unbelievable thermal properties," making it effective even at temperatures that soar as high as nearly 1,500 degrees Fahrenheit.

Manufacturing an ALD-based coating made of boron and other precursor gases, however, is exceptionally difficult to do, he said. Currently, technologists manufacture BNNTs by reacting boron powder with nitrogen and a small amount of ammonia in a chamber that must be heated to a scorching 2,552 degrees Fahrenheit — an expensive process. With ALD, ultrathin boron-nitride film could be laid in a chamber no hotter than 752 degrees Fahrenheit.

"Our team has studied the difficulties and think we understand why they're happening," Dwivedi said. As a result, he believes the team will succeed at depositing boron nitride on a silicon substrate by year's end. If subsequent tests at Goddard and the Langley Research Center possibly as early as next spring prove the material's effectiveness as a protective coating, he believes instrument designers could one day use the technology to coat mirrors, spacecraft buses, and other components.

"It doesn't matter what the substrate material is. This technology can coat anything. It is perfect point to point. There are so many applications for this technology," Dwivedi said. "The only thing limiting its use is your imagination." ❖

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Volume 8 • Issue 4 • Summer 2012

Inspiration from a Roll of Scotch® Tape

American author Robert Collier once noted that every tool, utensil, and instrument created by humans evolved from simple beginnings. Goddard scientist Maxim Markevitch would agree. After all, the inspiration behind his quest to build an X-ray mirror using a never-before-tried technique came from a roll of Scotch® tape.

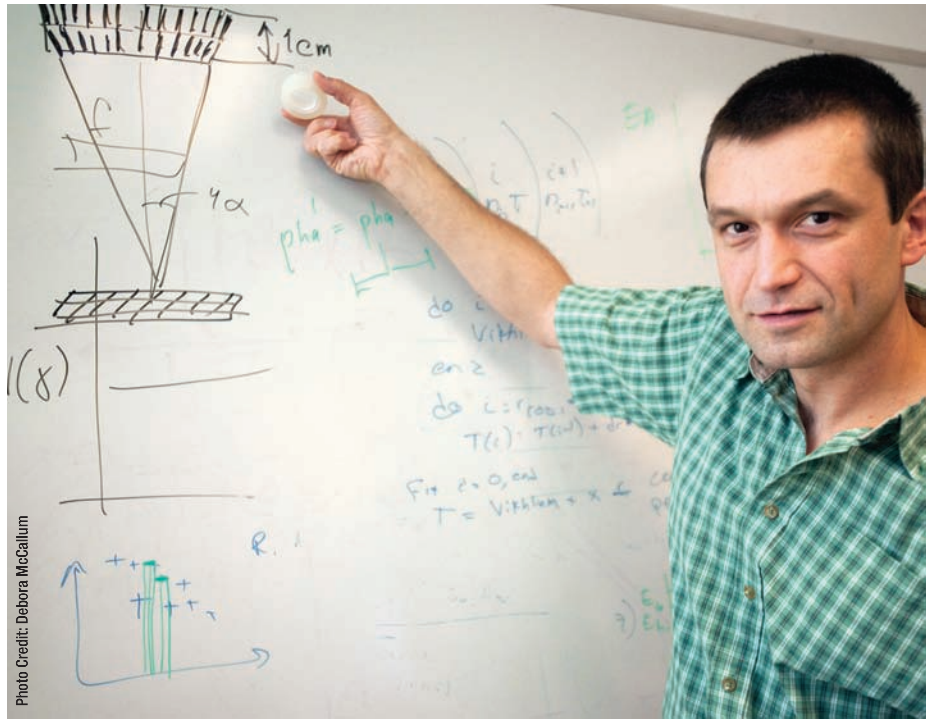

Photo Credit: Debora McCallum

Principal Investigator Maxim Markevitch is using R&D funding to pursue the feasibility of fashioning a low-cost X-ray mirror from plastic tape and tightly rolling it like the sticky adhesive ubiquitous in most homes and offices. The whiteboard drawing shows the shape of the X-ray mirror roll.

Markevitch, who has assembled a team of Goddard's preeminent experts in the field of X-ray optics, has begun investigating the feasibility of fashioning a low-cost mirror from plastic tape and tightly rolling it like the sticky adhesive commonly found in most homes and offices. "I remember looking at a roll of Scotch tape and thinking, 'was it possible to use the same design for capturing hard X-rays,'" Markevitch recalled. "I talked with a few people, and to my surprise, they didn't see any principal reasons why it couldn't be done."

With funding from NASA's Center Innovation Fund, the team now is pursuing Markevitch's "early-stage" idea and has already begun testing candidate materials that could be fashioned into a rolled mirror capable of collecting X-rays — in itself a challenging proposition. To capture these ever-elusive photons, the mirrors must be curved and nested inside a cylindrical optical assembly. The rounded geometry allows the high-energy light to graze their surfaces, much like a stone skimming the surface of a pond.

Motivating Markevitch is the fact that these highly specialized mirrors are time-consuming and expensive to build and assemble, despite efforts to dramatically reduce production costs (*CuttingEdge*, Winter 2012, Page 4). Making matters more demanding is the fact that X-ray observatories in the future likely will require much larger collecting areas, therefore requiring an even greater number of individual mirror segments that all must be nested, coated with layers of highly reflective materials, and perfectly coaligned inside their optical assemblies. "It's a lot of work fabricating these rigid shells and making sure they're properly aligned," he said.

The Science

The science Markevitch would like to pursue is one that would require a larger mirror. Over the past few decades, NASA has launched several X-ray observatories sensitive to lower-energy "soft X-rays," including the Chandra X-ray Observatory. They discovered and imaged the faint, diffuse X-ray signal from a variety of astrophysical sources dominated by thermal emission, such as galaxies and clusters of galaxies. Other missions, like Swift, were sensitive to higher-energy gamma rays, but they lacked imaging capabilities. "There remains a large and totally unexplored discovery space of faint, diffuse nonthermal astrophysical objects emitting at high X-ray energies," Markevitch said.

One class of objects waiting to be better understood is cosmic rays — highly energetic subatomic particles generated in deep space — that reside

Continued on page 11

A New Way to Track Formaldehyde

University of Maryland graduate student Heather Arkinson is shown here monitoring the In-Situ Airborne Formaldehyde Instrument, which she helped to demonstrate on a NASA DC-8. The image on the right shows the new air-sampling system that is more efficient at drawing in air and preventing particles from sticking and potentially contaminating formaldehyde measurements.

Goddard scientist Tom Hanisco is helping to fill a big gap in scientists' understanding of how much urban pollution — and more precisely formaldehyde — ultimately winds up in Earth's upper atmosphere where it can wreak havoc on Earth's protective ozone layer.

He and his team have developed an automated, lightweight, laser-induced fluorescence device that measures the levels of this difficult-to-measure organic compound in the lower troposphere and then again at much higher altitudes. The primary objective is determining how much pollution a storm can transport through convection and then using those insights to improve chemistry-climate models. "It's a major problem in modeling knowing how to treat transport and clouds," Hanisco explained.

In the spring, he flew the In-Situ Airborne Formaldehyde Instrument for the first time on a NASA DC-8 research aircraft, a former passenger airplane that can fly up to 43,000 feet.

Size and Sensitivity

"People like this instrument because it's small, sensitive, and easy to maintain," said Hanisco. The instrument weighs only 60 pounds, and therefore is easily installed inside other research aircraft, including NASA's ER-2, Global Hawk, and WB57, which fly at much higher altitudes. In addition, it's automated and doesn't require anyone onboard to operate it, Hanisco said.

Prior to its development, only one other airborne instrument could measure formaldehyde. That instrument, however, weighed 600 pounds, required an onboard operator, and used a less-sensitive measurement technique — absorption spectroscopy — to gather data.

"I've been doing laser-induced fluorescence on other molecules for a while," Hanisco said, explaining why he sought and received Goddard Internal Research and Development funds to apply the measurement technique to a formaldehyde-sensitive instrument. "Formaldehyde isn't measured well at high altitudes. There was a real need for improvement."

Continued on page 11

Atom Optics, *continued from page 3*

dation for any atom-based instrument created to fly in space, Saif said.

During the test, the team will insert a cloud of neutral rubidium atoms inside the 33-foot tower. As gravity asserts a pull on the cloud and the atoms begin to fall, the team will use its new laser system to fire pulses of light to cool them. Once in the wave-like state, the atoms will encounter another round of laser pulses that allow them to separate spatially. Their trajectories then can be manipulated so that their paths cross at the detector, creating the interference pattern.

The team also has formulated a potential gravitational-wave mission and submitted a proposal under the NASA Innovative Advanced Concepts (NIAC) program for additional funding. Similar to the Laser Interferometer Space Antenna (LISA), the concept calls for three identically equipped spacecraft placed in a triangle-shaped configuration. Unlike LISA, however, the spacecraft would come equipped with atom interferometers and they would orbit much closer to one another — between 500 and 5,000 kilometers apart, compared with LISA's five-million-kilometer separation. Should a gravitational wave roll past, the interferometers would be able to sense the miniscule movement.

"The science is compelling and now is the time to get atom interferometry tested and ready to go over the next five years," said Stanford University professor Leo Hollberg, a team member.

While the team awaits word on the NIAC funding, Saif said the team is moving forward. With Goddard R&D support, the team is working with Hollberg to improve the repeatability of atomic clocks. These clocks would measure the difference in the frequency of the laser light and that of the atom over a specific interval — in essence, acting like a phase meter that would assist scientists in identifying the faint gravitational-wave signal.

Such a device, also based on atom-optics technology, would allow the team to reduce the mission concept from three to two satellites, Saif said, further driving down the cost and complexity of designing, building, and launching a gravitational-wave detector in space.

"I'm at the point where I know the technology would work in space," Kasevich said. "But it presents a really complicated systems challenge that goes beyond our expertise. We really want to fly in space, but how do you fit this technology onto a satellite? Having something work in space is different than the measurements we take on Earth."

That's where Goddard comes in, Saif said. "We have experience with everything except the atom part," he said, adding that AOSense already employs a team of more than 30 physicists and engineers focused on building compact, ruggedized atom-optics instruments. "We can do the systems design; we can do the laser. We're spacecraft people. What we shouldn't be doing is reinventing the atomic physics. That's our partners' forte." ❖

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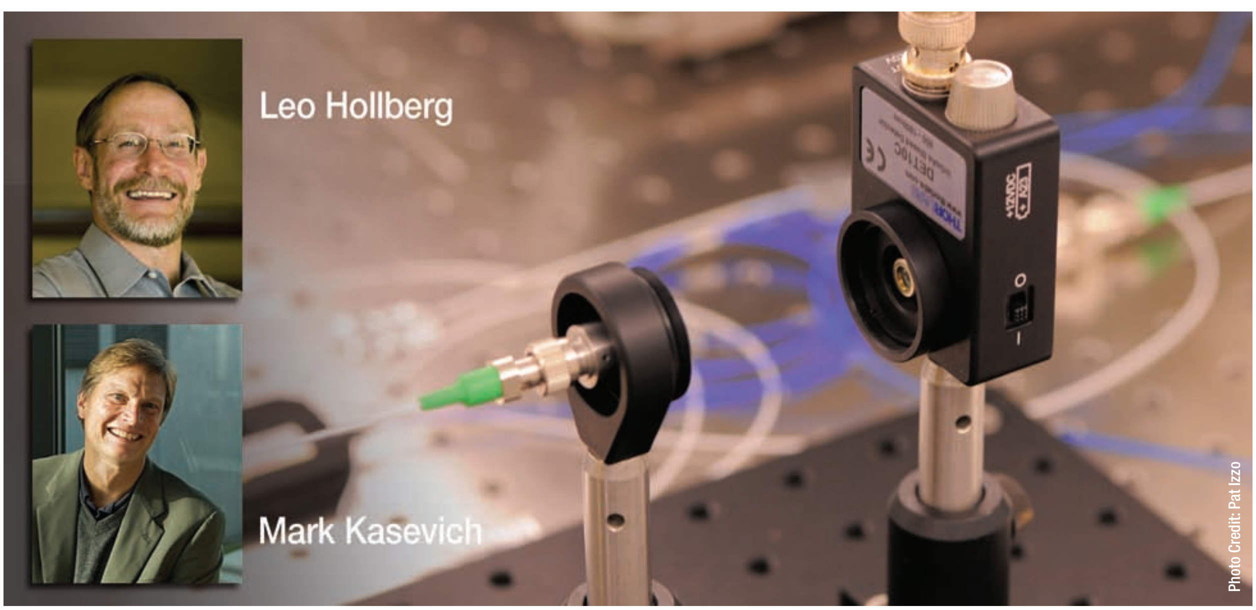

Shown here are the Stanford University collaborators and the Goddard-designed breadboard laser system to be tested in the drop tower.

Scotch® Tape, *continued from page 8*

in galaxy clusters and other large-scale structure in the universe. Scientists believe that cosmic rays and the magnetic fields between galaxy clusters can alter the physics within galaxy clusters. A better understanding of these physics could reveal more about the birth and evolution of the cosmos, Markevitch said.

To study cosmic rays, however, observatories would have to be tuned to hard X-rays. Although NASA's recently launched Nuclear Spectroscopic Telescope Array (NuSTAR) and Japan's New X-ray Telescope, also known as Astro-H, are sensitive to hard X-rays, Markevitch said they only "will graze the surface of this discovery space." Because the signal is so faint, only an imaging X-ray telescope with a collecting area 30 times larger than that of NuSTAR, working with current and future radio telescopes, could do the job, Markevitch said.

"However, to our knowledge, nothing of the kind is planned or even proposed in the U.S. or elsewhere because of the cost something like this presents," he said.

The only solution then is developing a new technology that would dramatically reduce the cost of building X-ray optics and increase the size of the light-collecting area. "If we can build a mirror that's big enough, this might be the way to go," he said.

Under his research plan, Markevitch, Takashi Okajima, Will Zhang, and Peter Serlemitsos are acquiring and testing candidate tape that would be coated on one side with a multilayer of reflective material and then wound into a roll, forming a large number of densely packed nested shells that are spaced by the varying thickness of the tape. "The collecting surface is automatic, it's rolled, self-supporting, and already aligned," Markevitch said. Multiple rolls then would be placed in an optical assembly, providing a much larger collecting area, or, in other words, a larger mirror.

"Maxim's Scotch tape idea is in an early stage," Zhang said. "In the next year, we will know whether it has a chance of working."

If it does, it could prove "game-changing for hard X-ray astronomy," Markevitch said. "It could significantly reduce the cost of building large mirrors, bringing within reach the possibility of building a mirror with 10 to 30 times greater effective area than current X-ray telescopes. To our knowledge, nobody is working on anything like this." ❖

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Formaldehyde, *continued from page 9*

With laser-induced fluorescence (LIF), a laser first illuminates the species of interest and "then you watch it fluoresce. It is a single photon-counting instrument," Hanisco said. Consequently, it's faster and more sensitive — even at concentrations in the parts per trillion, he said.

The DC-8 campaign in Kansas, sponsored by the National Center for Atmospheric Research's Deep Convective Clouds and Chemistry Project, bore out the wisdom of his pursuit, proving that his instrument offered a factor-of-10 improvement in size, sensitivity, and complexity. During that campaign, a DC-8 flew as low as 500 feet above the ground and sampled air entering a storm. It then spiraled up to 30,000 to 40,000 feet and measured the air coming out at the top of the storm.

The instrument found that 30 to 40 percent of the formaldehyde produced in the "boundary" layer — the lowest part of the troposphere closest to Earth's surface — was transported to the upper troposphere during storms. "That number is a rough guideline, but we didn't have it before. Every storm is different, but knowing how much air gets through is a big step forward."

Hanisco attributes the instrument's success to its greatly simplified design and a new fiber-laser system that is smaller and less expensive than those used in other LIF-type instruments. He also attributes its success to a new air-sampling system, which features a glass- and Teflon-coated tube that draws in and directs air into the instrument's detection cell. Though the polymer-coated sampling system allows air to flow quickly, its surface prevents particles from sticking — particularly useful because they could corrupt results. "We had to work hard to ensure that the sampling system was every bit as good as the detection," Hanisco said.

Hanisco anticipates many other flight opportunities in the future. "There was a real need for this instrument. There aren't a lot of instruments out there doing this." ❖

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A Mission of Firsts

NASA on Track to Deliver Critical Lasercom Hardware

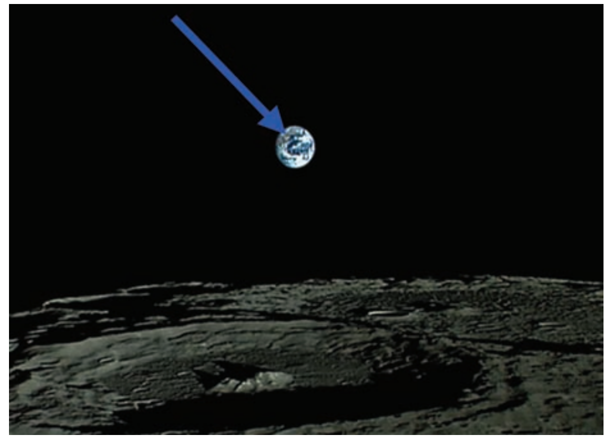
NASA is on track to achieve a major milestone in its quest to demonstrate for the first time a new laser-communications (lasercom) system capable of 622-megabit-per-second data speeds from lunar distances, six times the current state-of-the-art from the Moon.

A Goddard-led team, which includes MIT Lincoln Laboratory, has begun environmental testing of the Lunar Laser Communications Demonstration (LLCD) experiment. The team expects to deliver the payload to the Ames Research Center for integration onto the Lunar Atmosphere and Dust Environment Explorer (LADEE) by mid-October. LADEE's principal mission is characterizing the Moon's wisp-thin atmosphere and dust environment.

"We're on track. This is exciting, especially since this project is a mission of firsts," said LLCD Project Manager Don Cornwell. "It's the first time the Wallops Flight Facility has launched a mission to the Moon and, of course, the first to demonstrate laser communications from lunar distances. This is an important milestone for us."

Built by MIT-Lincoln Laboratory, the payload consists of a four-inch telescope and a half-watt laser mounted on a precision gimbal. Its primary mission when NASA launches the LLCD-equipped LADEE on a Minotaur-5 launch vehicle in August 2013 is proving fundamental concepts of laser-based communications. The experiment is expected to operate during the 30 days of spacecraft commissioning — enough time to prove the value of laser communications and lay the foundation for NASA's fully operational system demonstration, the Laser Communications Relay Demonstration (LCRD) mission, in 2017.

LCRD, funded by NASA's Office of the Chief Technologist, will operate for up to five years. To be housed on a commercial communications satellite built by Space Systems/Loral, of Palo Alto, Calif., the payload will communicate with two specially



This artist's rendition shows the distance between NASA's Lunar Laser Communications Demonstration experiment and ground stations on Earth.

equipped ground stations in California and New Mexico. MIT Lincoln Laboratory and NASA's Jet Propulsion Laboratory (JPL), both world-renowned experts in laser communications, are providing significant portions of LCRD's ground and space segments, although Goddard will integrate and test the system prior to flight.

LLCD, on the other hand, will communicate with three ground stations. MIT Lincoln Laboratory, JPL, and most recently, the European Space Agency in Tenerife, Spain, are providing the equipment, each different from the other, Cornwell said. Lincoln Laboratory's ground terminal, however, is expected to be nearly 10 times more efficient than any optical receiver ever demonstrated at these high data rates. It incorporates four 17-inch diameter telescopes, each with its own high-performance photon-counting light detector.

For NASA scientists, high-speed data communications promised by the lasercom technology can't come too soon. Current science missions are constrained by the amount of data they can communicate over the long distances to the Moon and beyond. ❖

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